Finite Element Analysis and Experimental Evaluation of Bioyield Probes for Measuring Apple Fruit Firmness

R. Lu, A. K. Srivastava, H. A. A. Ababneh

Abstract. *The bioyield phenomenon occurs during compression of an apple fruit by a mechanical probe, which results in cell failure without tissue rupture. Because of its minimal damage to the fruit, the bioyield phenomenon can be used for nondestructive or minimally destructive evaluation of fruit firmness. The objective of this research was to develop a probe for better measurement of the bioyield point for apple fruit to assess their firmness. The research was based on the premise that the soft-tipped probe would produce constant contact and a uniform pressure distribution over the contact area of the fruit and thus enhance the detection of the bioyield point. The finite element method was used to analyze the contact stress distribution in the apple fruit resulting from the compression of soft bioyield probes of different sizes, thicknesses, and elastic moduli. The modeling results showed that to achieve uniform contact pressure, the bioyield probe should have a soft tip with an elastic modulus comparable to or less than that of the fruit and a thickness greater than 2 mm. Six bioyield probes, along with the standard destructive Magness-Taylor (MT) firmness tester, were tested on four apple cultivars ('Gala,' 'Golden Delicious,' 'Fuji,' and 'Red Delicious'). Probe size (between 6.4 mm and 11.1 mm) did not affect the correlation between force at the bioyield point and MT firmness. The probe with a 1.6 mm thick tip, which was undesirable based on the finite element modeling, had a high missing rate (13%) of detecting the bioyield point, compared to that (2%) for the other five probes with thicker soft tips. The 6.4 mm probe with a 3.2 mm thick rubber tip and an elastic modulus of 3.27 MPa had a good correlation (r = 0.828) with MT firmness measurement. Since the smaller probe causes minimal damage to the fruit, it is a better choice for the bioyield measurement.*

Keywords. *Apples, Bioyield, Firmness, Fruit, Nondestructive measurement.*

Firmness is an important parameter in assessing the maturity and quality of many horticultural products including apples, pears, and peaches. It is critical to measure and monitor fruit firmness at various stages of fruit production and postharvest handling and marketing so that appropriate management procedures can be taken to maintain or enhance the quality of fruit. Currently, fruit growers, packers, inspectors, and retailers routinely use the destructive Magness-Taylor (MT) firmness tester to measure the firmness of fruit for determining their quality grade. The MT tester measures the maximum forces required for a cylindrical steel probe to penetrate the fruit, which renders the fruit unmarketable after testing. Different versions of MT testers are currently in use, including low-cost handheld mechanical testers based on a calibrated spring, portable testers equipped with an electronic gauge, and more expensive testers that are coupled to a universal testing machine (Lu and Abbott, 2004).

Considerable research has been reported on developing nondestructive firmness testing techniques, including quasi-static force/deformation, impact, vibration, sonic, optic, etc. (Abbott et al., 1997; De Belie et al., 2000; Hung et al., 2001). Several impact, acoustic, and force/deformation devices have been recently developed for measuring fruit firmness (Garcia-Ramos et al., 2003; Mizrach et al., 1997; Prussia et al., 1994; Shmulevich et al., 2003; Sugiyama et al., 1998). These devices are expensive and may not be appropriate for laboratory or orchard uses. Further, since these nondestructive techniques measure mechanical properties that are different from those measured by the MT tester, their correlation with MT firmness, especially for firm fruits such as apples, is low or inconsistent (Shmulevich et al., 2003). For field and laboratory applications, a compact, portable tester that is low in cost is needed. Efforts have thus been made to develop low-cost mechanical testers for larger fruits (Fekete, 1993; Bellon et al., 1993; Takao and Ohmori, 1994) and small fruits (Timm et al., 1996). These mechanical testers measure the force/deformation of the fruit under compression of a steel probe. In order to minimize potential damage to the fruit, the force and/or displacement of the probe must be accurately controlled and measured, and the deformation of the fruit must be small (e.g., within 0.2 to 0.3 mm). Since fresh fruits such as apples have a curved, sometimes irregular, surface, the probe may not be in full contact with the fruit until it has reached a certain amount of

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deformation. With the deformation being small, this could potentially cause large errors in measurements. In addition, a smaller size probe is often preferred to avoid degrading the fruit. This could have further implications in obtaining consistent and reliable measurements because the contact area is small and, possibly, changes during compression of the probe against the fruit.

When an apple fruit is subjected to compressive loading of a cylindrical probe, we often observe from the recorded force/displacement curve a sudden drop or no increase in force as the displacement increases before the fruit tissue is ruptured. This phenomenon is characteristic of many biological materials and is referred to as the bioyield phenomenon (Mohsenin, 1986). The bioyield phenomenon occurs as the tissue cells start to fail; it causes no visible damage on the surface of the fruit and negligible browning of the fruit tissue under the skin. Thus, Mohsenin et al. (1965) proposed using force at the bioyield point (hereafter designated as F_{by}) as a possible nondestructive method to measure fruit firmness. Mohsenin et al. (1965) developed a mechanical tester that used a steel probe of 6.4 mm (1/4 in.) diameter for detecting the bioyield point of apple fruit.

It is well known from the classical Hertz or Boussinesq contact theory (Mohsenin, 1986) that the contact (normal) stress is generally non-uniform within the contact region between two elastic bodies. When two convex elastic bodies are in contact (the Hertz contact problem), the stress distribution is elliptic, with the maximum normal stress occurring at the center of the contact area. In the case of Boussinesq contact, where a flat rigid probe is in contact with a semi-infinite elastic body, stress concentration occurs at the edge of the contact region. The compression of a cylindrical steel probe against an apple fruit is similar to the Boussinesq contact problem. Hence, the tissue failure would propagate from the outside of the contact region towards the center. Observed from the force/deformation curve are a series of minute failure events taking place over a range of deformation (fig. 1). This could be a problem for detecting the bioyield point consistently and reliably. However, the situation can be improved if the rigid probe is tipped with soft material that can sustain large elastic deformation at low load. The soft probe would easily conform to the contact surface of the fruit and maintain a constant contact area between the probe and the fruit during loading. The stress/strain distribution over the contact area would be more uniform, and this means that the fruit tissue beneath the contact region would fail simultaneously rather than gradually. The simultaneous tissue failure would result in a conspicuous drop in force at the bioyield point, thus facilitating the detection of the bioyield point (fig. 1). Constant contact and uniform contact stress are thus conducive to obtaining consistent measurements of fruit firmness, especially when the fruit are tested under small force and/or deformation.

This article reports on results from the theoretical analysis and experimental evaluation of mechanical probes tipped with soft material for measuring F_{by} to estimate apple fruit firmness. The first part of this article presents a theoretical background on using the finite element (FE) method to analyze the contact stress/strain distribution in apples under compressive loading of the bioyield probe. Findings from the FE analysis of different probe designs (i.e., the size, thickness, and modulus of elasticity of the tip) are discussed in the context of determining optimal probe parameters. The second part of this article reports on experimental results from the evaluation of different bioyield probes for measuring bioyield parameters (i.e., F_{by}, displacement, slope, and energy at the bioyield point) of apples in comparison with the standard destructive MT firmness tester.

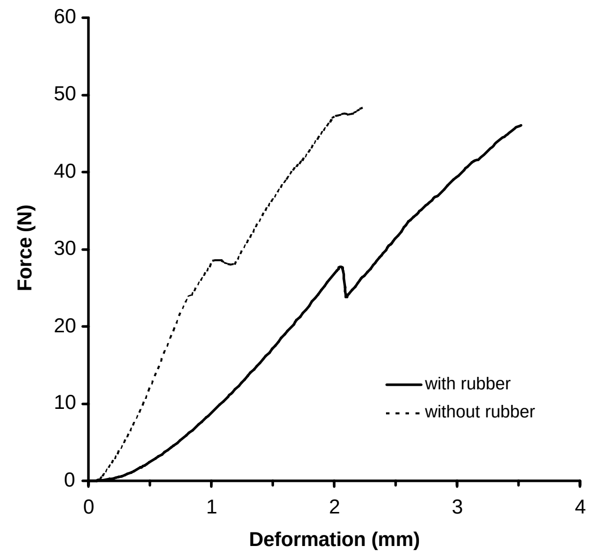

Figure 1. Force-deformation curves for an apple fruit under compression of a cylindrical steel probe with (solid line) and without (dotted line) a rubber tip. The probe without rubber did not produce a sharp drop in force at the bioyield point, whereas the probe with rubber produced a smooth curve and a sharp drop at the bioyield point.

Finite Element Analysis of Bioyield Probe Designs

The FE method was used to investigate the mechanical responses of an apple fruit under compressive loading of a cylindrical probe with a soft tip. We were interested in how different probe designs, i.e., probe size and the thickness and modulus of elasticity of the soft tip, would affect the stress/strain distribution within the contact area of the fruit and thus F_{by} measurements. Rubber was selected for the probe tip because it has a high degree of elastic deformability and can achieve constant contact with the fruit at lower load. Finite element analyses were performed using the commercial software package MARC (MARC, 2000). As discussed earlier, a uniform stress distribution within the contact area of the fruit is favorable for measuring F_{by}. Hence, the goal of our FE analyses was to determine an optimal probe design that would produce a uniform stress distribution in the contact region and minimize potential damage to the fruit.

Finite Element Modeling

In developing an FE model for analyzing the contact between the probe and the fruit, the apple fruit was assumed to be axisymmetric with respect to the contact center. This assumption is reasonable in view of the relative sizes of the bioyield probe and apple fruit. As a result of this assumption, the three-dimensional contact problem was reduced to a two-dimensional problem, which greatly simplified the finite element modeling.

Model Apple

The profile of the cross-section of an apple (92 mm in diameter and 73 mm in height) was traced and used as the basis for developing the FE model apple. The model apple consisted of two isotropic materials: the fruit skin and the flesh. The core of an apple has mechanical properties different from those of the cortex or flesh (Lu and Abbott, 1997). However, since the contact stress/strain distribution is largely limited to a local region close to the contact area, the effect of the core can be neglected. The fruit skin was assumed to be 0.5 mm thick and elastic, with a modulus of elasticity of 10.0 MPa and Poisson's ratio of 0.3 (Clevenger and Hamann, 1968). The fruit flesh was treated as a linear viscoelastic material. The Poisson's ratio for the flesh was chosen to be 0.3 (Mohsenin, 1986). The viscoelastic properties of the fruit flesh were obtained from stress relaxation tests on 15 cylindrical specimens (20.0 mm in diameter and 12.4 mm in height) taken from 15 'Golden Delicious,' 'Red Delicious,' and 'Fuji' apples. MT firmness of these apples was estimated to be about 60 N, which was considered medium firm, based on compression tests of tissue specimens. The tissue specimens were first compressed to 10% strain level at 0.5 mm/s loading rate using an Instron universal testing machine and then held at that strain level for 120 s. The stress relaxation curves from the 15 specimens were averaged, and the following Maxwell model was then used to fit the average stress relaxation curve:

$$\sigma(t) = \varepsilon_o\left(E_1 e^{-t/\tau_1} + E_2 e^{-t/\tau_2} + E_3\right) \quad (1)$$

where σ is the compressive stress (MPa); ε_o is the initial strain (0.10); t is time (s); E_1, E_2, and E_3 are the stiffnesses of three spring elements with values of 0.488, 0.590, and 1.13 MPa, respectively; and τ_1 and τ_2 are the first and second time constants with values of 2.27 s and 45.6 s, respectively. A detailed description of the experimental procedure for measuring the viscoelastic properties of apple fruit can be found in Ababneh (2002).

The model apple described above was used for studying the effect of different probe and tip parameters on bioyield measurements. In addition, a separate model apple was created, with data (i.e., fruit size, shape, and mechanical properties) collected from a 'Fuji' apple, to validate the FE model against the experimental force/deformation curve of the fruit under the compression of a bioyield probe. The Fuji apple, 81 mm in equatorial diameter and 70 mm in height, was tested using a 6.4 mm steel probe with a 3.2 mm thick rubber tip of 3.27 MPa elastic modulus. The validation model apple had an F_{by} value of 27.2 N and an MT firmness measure of 49.4 N; its modulus of elasticity was 4.01 MPa, as determined from the compression test on a cylindrical apple specimen (20 mm in diameter and 12.4 mm in height). The viscoelastic parameters in equation 1 for the apple were: E_1 = 1.51 MPa, E_2 = 0.50 MPa, E_3 = 0.53 MPa, τ_1 = 1.14 s, and τ_2 = 13.87 s.

FE Formulation

Since the contact problem described here could not be solved analytically, the FE method was used to obtain approximate solutions. The general procedure for developing an FE model has been well documented in many textbooks (Segerlind, 1984). The model apple was first discretized into 793 triangular elements for the fruit flesh and 46 quadratic elements for the skin (fig. 2). Because of the symmetry assumption, only one quarter of the model apple is shown in figure 2. The probe consisted of a rigid part and a soft tip. The soft tip was made of rubber material, which is generally incompressible and exhibits nonlinear behavior under large deformation. To accurately describe the nonlinear elastic behavior of a rubber material under large deformation, a nonlinear model is required. However, for practical applications, the rubber material selected for the probe tip should be not significantly softer than the fruit in order to avoid the instability problem during compression. Further, the bioyield phenomenon often occurs at a low level of deformation in the fruit. Hence, it was reasonable to assume that the tip material was linearly elastic with a Poisson's ratio of 0.48, close to that for incompressible materials. Triangular elements were used to generate the FE mesh for the soft tip. Approximate linear functions were used to describe the displacements in each element in terms of nodal values. The governing equation for the quasi-static contact problem was expressed in the following general form in terms of nodal displacements:

$$\boldsymbol{KU} = \boldsymbol{f} \quad (2)$$

where $\boldsymbol{K}$ is the system stiffness matrix, $\boldsymbol{U}$ is the displacement vector of the element nodes, and $\boldsymbol{f}$ is the force vector. By imposing appropriate boundary conditions for the selected nodes in the contact region, the system of linear equations (eq. 2) were solved numerically, which gave displacements for individual element nodes. The stress/strain components for each node were then calculated from the nodal displacements by using appropriate equations (Segerlind, 1984). In this study, no penetration constraint was applied to the contact between the soft tip and the fruit based on the solver constraint technique (MARC, 2000).

FE Simulations

After the FE model was established, simulations were performed to investigate the effect of various factors on the stress/strain distribution in the contact region. The diameter and thickness of the rubber tip and its modulus of elasticity were three major factors to be investigated in the FE analysis. Other factors included the tip edge shape (sharp versus round), fruit size, and fruit skin properties. Since these latter factors only had minor effects on the stress/strain distribution, they are not further discussed here and readers are referred to Ababneh (2002).

Finite element simulations were performed at 0.5 mm/s loading rate. The effect of tip elasticity was investigated for an 11.1 mm (7/16 in.) probe, the same size as that of the MT probe. The modulus of elasticity ranged from 2.5 MPa to a rigid body (infinitely large elasticity). Further, seven probe sizes were also considered, ranging from 4.8 mm (3/16 in.) to 14.3 mm (9/16 in.). Finally, tip thickness between 0 and 5 mm was investigated to determine how this factor influences the normal contact stress distribution. Table 1 summarizes pertinent information on probes and tips that were used in the FE simulations.

Finite Element Modeling Results

Model Validation

The FE model was validated by comparing the force/deformation (F/D) curve generated from the FE modeling with that obtained from the compression test on the 'Fuji' apple. The F/D curve generated by the FE modeling matched the

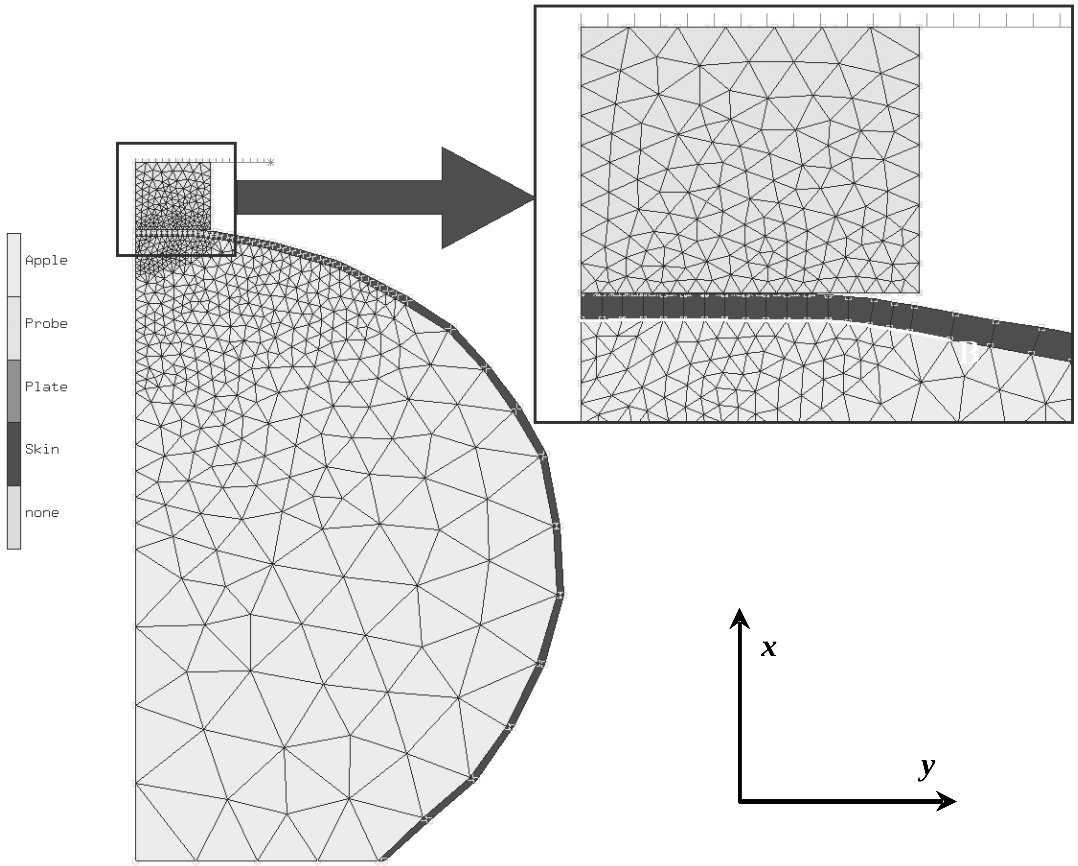

Figure 2. Finite element model showing the contact between a cylindrical rigid probe with a soft tip and the model apple. The fruit skin and flesh were treated as two different materials.

Table 1. Summary of the parameters of bioyield probes used in the finite element analysis of the contact stress distribution in apple fruit.

Parameter	Value
Probe size (mm)	4.8, 6.4, 7.9, 9.5, 11.1, 12.7, 14.3
Tip modulus of elasticity (MPa)	2.5, 4.0, 5.0, 7.5, 10.0, 15.0, 25.0, 1000, ∞
Tip thickness (mm)	0.0, 1.0, 2.0, 3.0, 4.0, 5.0

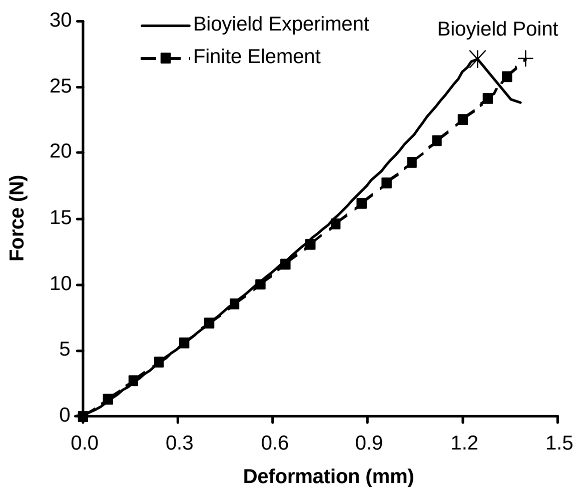

Figure 3. Comparison of the finite element modeling results with the experimentally measured force/deformation curves for a 'Fuji' apple under the compression of a soft-tipped bioyield probe (diameter = 6.4 mm, tip thickness = 3.2 mm, and tip elasticity = 3.27 MPa).

curve from the experimental test remarkably well up to 0.8 mm combined deformation for both the fruit and the rubber tip (fig. 3). As the load further increased, the difference between the FE-modeled and experimental F/D curves started to increase. At the bioyield point, the FE-modeled displacement was about 15% greater than that from experiment. This relatively large difference at large displacement was likely due to the increasingly nonlinear behavior of the tip material and the apple fruit. Overall, the FE model well described the mechanical response of the apple fruit under contact loading.

The FE analysis showed that when an apple fruit was subjected to contact loading, the normal stress was dominant in comparison with the shear stress. Hence, it is reasonable to expect that normal stress is primarily responsible for the bioyield failure of fruit tissues. Corresponding to an F_{by} value of 27.2 N for the test apple, the FE-predicted maximum normal stress took place just beneath the skin at 0.51 MPa. The normal contact stress at the contact region of the fruit was uniformly distributed.

Based on the model validation results and experimental testing of additional apples for F_{by} and MT firmness, the bioyield point for the FE model apple was assumed to take place when the normal contact stress reached 0.64 MPa. This stress level corresponded to the average MT firmness of 62 N (or 14 lbs. force) for the test apples. The following FE modeling results are discussed in reference to this critical stress level.

Tip Elasticity

The FE modeling results (fig. 4) demonstrated that the normal contact stress distribution became increasingly uniform as the elasticity of the rubber tip decreased from an infinitely large value (rigid) to 2.5 MPa, about half of that for the model apple. The degree of stress concentration, calculated as the ratio of the difference between the maximum contact stress and the bioyield stress of 0.64 MPa to the bioyield stress, increased from 1.7% for E = 2.5 MPa to 28.3% for E = 10.0 MPa. Clearly, a softer tip is desirable for generating the uniform stress distribution. However, when the tip is too soft, it is also susceptible to warping due to large deformation before reaching the bioyield point. The results in figure 4 suggest that tip elasticity should be comparable to or less than that of the apple fruit to achieve a relatively uniform normal stress distribution at the bioyield point.

Probe Diameter

The diameter of the probe is closely related to the bruise volume when the bioyield failure occurs to the fruit. The FE simulations indicated that the maximum deformation at the center or the bruise depth was linearly related to the diameter of the probe. The volume of the bruised tissue would be proportional to the cubic power of the diameter. Larger probes would increase the bruise volume during the test and, therefore, are undesirable. Figure 5 shows how different probe sizes affected the normal stress distribution at the bioyield point. The tip used in the FE modeling had an elastic modulus of 3.27 MPa. Consistent, uniform stress distributions were obtained for all test probes, with sizes ranging from 4.8 mm (3/16 in.) to 14.3 mm (9/16 in.). Hence, for practical purposes, a smaller size probe (e.g., 6.4 mm) is recommended for measuring F_{by}.

Tip Thickness

With the same rubber material, tip thickness could affect the stress/strain distribution in the contact region. Figure 6 shows FE modeling results for an 11.1 mm probe with tip thickness ranging from 0 mm (rigid) to 5 mm and an elastic modulus of 3.27 MPa. When the tip was 1 mm thick, the maximum stress was more than 50% higher than the stress at the contact center (0.64 MPa). When the tip thickness was 2 mm, the normal contact stress was relatively uniform over the entire contact area; the standard deviation was below 4.2% of the average normal stress in the contact area. As the tip thickness increased to 3 mm and higher, no noticeable changes in the stress distribution were observed. In conclusion, a minimum of 2 mm thickness is needed for uniform contact stress in the contact area when the tip elasticity is lesser than that of the fruit.

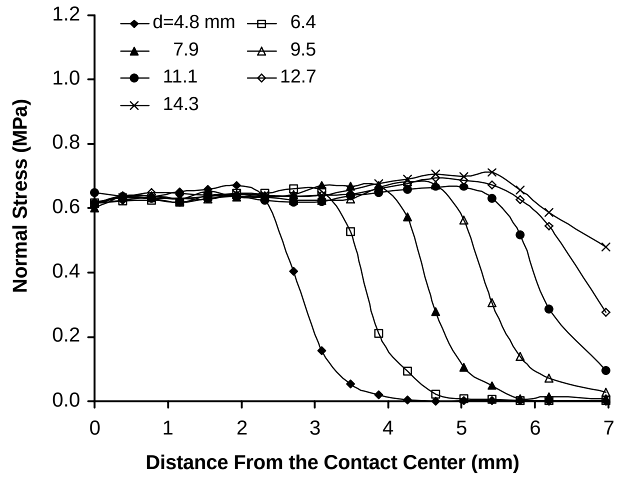

Figure 5. Effect of probe diameter (d) on the normal contact stress distribution at the bioyield stress level of 0.64 MPa. The bioyield probe had a soft tip with a thickness of 3.2 mm and elastic modulus of 3.27 MPa.

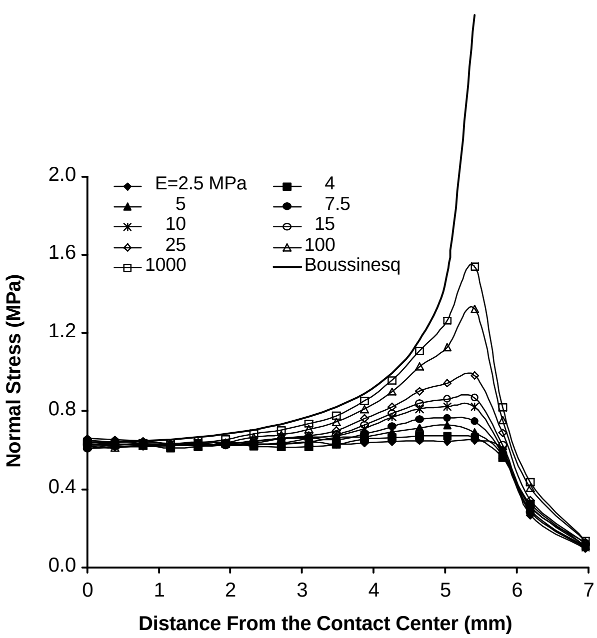

Figure 4. Normal stress distributions on the contact area of the apple under compression of an 11.1 mm probe with a tip of different elastic moduli.

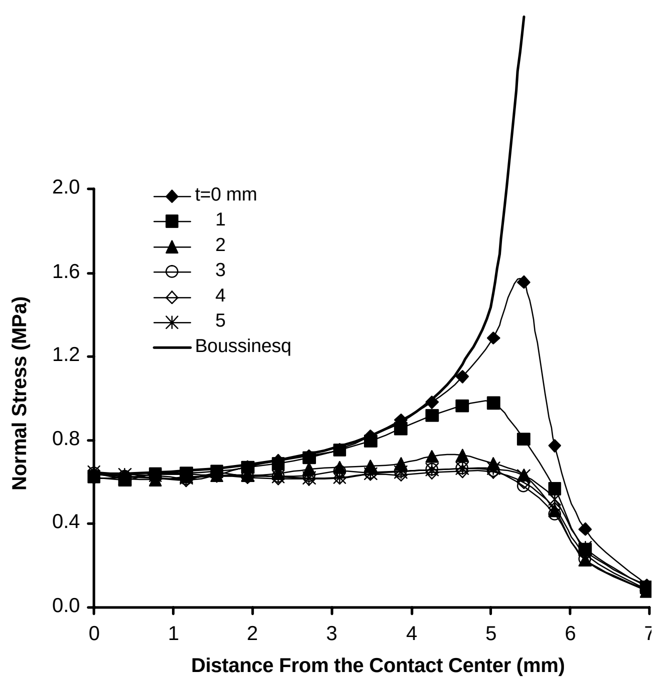

Figure 6. Effect of tip thickness on the normal contact stress distribution under compression of an 11.1 mm probe with a tip thickness of 3.2 mm and elastic modulus of 3.27 MPa.

Experimental Evaluation of Biyield Probes

Methods and Procedure

Based on the FE analysis of the tip parameters, we tested six different bioyield probes for measuring F_{by} in comparison with MT firmness. Three probe sizes and two thickness-to-diameter ratios were used. Based on the FE modeling findings, five of the six probes were considered good and one was not because it had a tip thickness of 1.6 mm. The dimensions of these probes and the rubber tips are summarized in table 2. The modulus of elasticity for these tips was 3.27 MPa based on the compression test.

Apple Samples

A total of 640 apple samples (160 each of 'Golden Delicious,' 'Red Delicious,' 'Gala,' and 'Fuji') were used in the experiment. These apples were harvested from Clarksville Horticultural Experiment Station, Michigan State University, in September and October of 2001 and were stored in a controlled atmosphere (CA) environment prior to the testing. Bioyield and MT firmness tests were conducted after the fruit were kept at room temperature (approx. 23°) for 24 h after removal from CA storage. On each test apple, two locations on the opposite sides around the equatorial area of the fruit were selected for both bioyield and MT tests. For each location, the MT test site was first selected and marked, followed by the marking of three bioyield test sites equally distributed around the MT test site. Each bioyield site corresponded to one probe. This arrangement of MT and bioyield test sites minimized the effect of the property variation within individual apples on bioyield and MT measurements.

Bioyield and MT Tests

Both bioyield and MT tests were conducted using an Instron universal testing machine. Each of the six bioyield probes was mounted onto the Instron to collect bioyield data from the marked test sites on individual fruits at a loading rate of 0.5 mm/s. The F/D curves were recorded for each probe test. The bioyield test was stopped when the force dropped by 0.01% of the current load level. After the bioyield tests had been completed, MT firmness tests were performed with a standard 11.1 mm probe at the same loading rate of 0.5 mm/s. The skin was first removed from the fruit to minimize its effect on firmness measurements. The MT test was stopped after the probe penetrated the fruit for 9 mm.

Data Analyses

Relevant information was extracted from the F/D curves obtained from the bioyield and MT tests. For the bioyield test, we obtained F_{by}, deformation (D_{by}), energy or work (E_{by}), and the secant slope (S_{by}) from the start point of contact to the bioyield point. Maximum forces from the F/D curves recorded during the MT test were used as a measure of fruit firmness. Linear regression analyses were performed on relating F_{by} for each bioyield probe to MT firmness. In addition, correlations between other bioyield parameters and MT firmness were also calculated.

Table 2. Parameters of six bioyield probes used for the bioyield measurement of apple fruit firmness.[a]

Probe Size	Probe Diameter (d, mm)	Probe Thickness (t, mm) for t/d = 0.5	for t/d = 0.25
Small	6.4	3.2 (SK)	1.6 (SN)
Medium	9.5	4.8 (MK)	2.4 (MN)
Large	11.1	5.6 (LK)	2.8 (LN)

[a] Symbols in parentheses designate probes: SK = small thick, SN = small thin, MK = medium thick, MN = medium thin, LK = large thick, and LN = large thin. The tips had an elastic modulus of 3.27 MPa.

Analysis of Bioyield and MT Test Results

Bioyield tests resulted in a well-defined bioyield point for the majority of the test fruit (fig. 1) for all probes except the small thin (SN) probe (see table 2 for details) whose tip was only 1.6 mm thick. Overall, the force drop at the bioyield point was more pronounced for firm apples than for softer apples. The bioyield point was detected for 98% of the test samples by the five probes with tip thickness greater than 2.0 mm. The 12 apples whose bioyield point was not detected came from one set of 40 'Red Delicious' apples that were left at room temperature for four days. These 12 apples were cut in half to visually inspect their flesh after the bioyield and MT tests had been completed. It was found that these apples appeared to have developed a mealy texture and brownish color. Mealiness is a physiological disorder that results in dry, soft fruit after long periods of cold storage. The SN probe, however, was only able to detect the bioyield point for 87% of the apple samples. The considerably lower detection rate for the SN probe confirmed the FE findings that the probe with a soft tip of less than 2 mm thickness would produce stress concentrations in the contact area. This non-uniform stress distribution would lead to gradual failure of the fruit tissue in the contact region, making it more difficult to detect the bioyield point.

Regression results between MT firmness and F_{by} for the six probes are summarized in table 3. Results for the small probe with either thin or thick soft tip for the pooled data of the four apple cultivars are further shown in figures 7 and 8. Overall, the correlation between MT firmness and F_{by} ranged between 0.792 and 0.828 for the six probes. These results compare favorably with those ($r < 0.60$) obtained with the sonic or impact technique (Shmulevich et al., 2003). MT firmness is variable within individual apple fruit. In fact, the correlation between MT firmness measured from the two opposite sides of the same apples was only 0.919 for all 640 apples. Although no statistical comparisons could be made between the regression results for the six probes, two general trends should be mentioned. First, for the same size probes, the thick tip had a slightly higher correlation coefficient than the thin tip. Second, the correlation coefficient tended to improve slightly as the probe size decreased. While it remains to be further validated whether these two

Table 3. Correlation coefficients of Magness-Taylor (MT) firmness with force, deformation, slope, and deformation energy at the bioyield point.

Probe[a]	Force (F_{by})	Deformation (D_{by})	Slope (S_{by})	Energy (E_{by})
LK	0.803	0.526	0.753	0.708
MK	0.819	0.560	0.744	0.726
SK	0.828	0.571	0.733	0.740
LN	0.792	0.333	0.749	0.604
MN	0.801	0.309	0.746	0.610
SN	0.806	0.249	0.712	0.615

[a] SK = small thick, SN = small thin, MK = medium thick, MN = medium thin, LK = large thick, and LN = large thin.

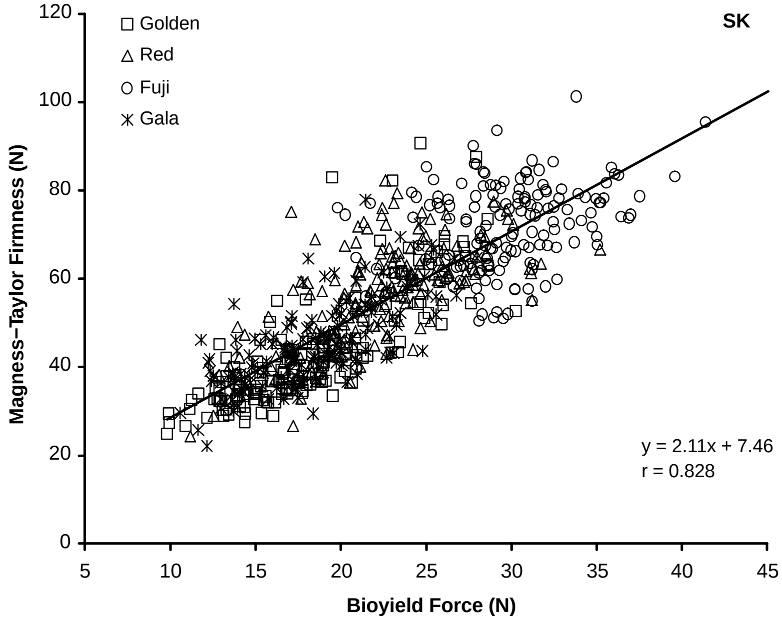

Figure 7. Correlation of the Magness-Taylor firmness of four apple varieties with force at the bioyield point measured by the small thick (SK) probe.

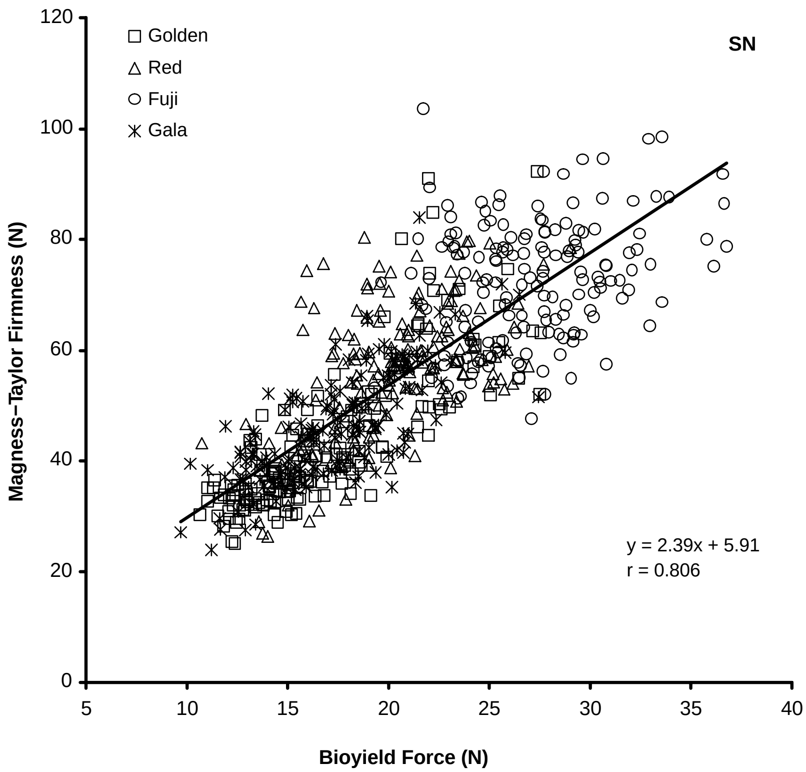

Figure 8. Correlation of the Magness-Taylor firmness of four apple cultivars with force at the bioyield point measured by the small thin (SN) probe.

observed trends are statistically significant, they seem to be compatible with the FE analysis and with our premise that uniform contact stress is helpful for detecting F_{by} and improving measurement consistency.

The correlations between MT firmness and other bioyield related parameters (i.e., deformation, energy, and slope) are presented in table 3, along with that for F_{by}. The correlation coefficients with non-F_{by} parameters are considerably lower than that with F_{by} for their corresponding probes. Hence, bioyield force is a better parameter for measuring fruit firmness. Again, the bioyield probes with thick tips had higher correlation coefficients than those with thin tips, which is especially pronounced for the bioyield deformation. Among the six probes, the small thick (SK) probe had the highest correlation (r = 0.828) with MT firmness for three of the four bioyield parameters (i.e., F_{by}, D_{by}, and E_{by}), even though its statistical significance has yet to be tested. Since the small probe produced smaller bruises during the bioyield measurement than the larger probes, it should be the probe of choice.

Discussion

This research was based on the premise that the uniform normal contact stress distribution over the contact area between an apple fruit and a probe with a soft tip is conducive to the detection of the bioyield point of apple fruit. Finite element analyses of different bioyield probe designs provided quantitative information on selecting appropriate probe tip parameters, including size, thickness, and elastic modulus. An optimal bioyield probe should have a soft tip with a proper thickness (>2 mm) and a modulus of elasticity comparable to or less than that of the apple fruit. The FE modeling further suggested that a small probe tended to yield a more uniform normal contact stress distribution than a larger probe. The subsequent experiment on the six bioyield probes showed that the small (6.4 mm) probe was as good as or even better than the larger probes for measuring fruit firmness. Our research demonstrated that the soft-rubber tipped probe is superior to the rigid probe in detecting the bioyield point and tends to provide better correlation with MT firmness.

When an apple became too soft or mealy, it often did not show the bioyield phenomenon at all. This could have some implication in using the bioyield probe to detect and sort out those soft, mealy apples. Since only limited mealy apples were encountered in this research, further investigation of the bioyield probe for detecting mealy apples would certainly be helpful.

Past research on nondestructive or minimally destructive mechanical probes used rigid probes and required accurate measurement and control of both force and deformation of the fruit. In comparison, the bioyield probe used in this research provides better contact with the fruit and only needs to measure force at the bioyield point. These features are advantageous in obtaining more consistent, reliable measurements of fruit firmness.

The bioyield point often occurred when the deformation of apple fruit was less than 0.5 mm. With the 6.4 mm probe, the bruised volume was small and could not be seen. Hence, the bioyield test can be used to monitor the firmness change when fruit are still on the tree or during postharvest handling and storage. Based on the findings of this research, we recently developed and tested a portable bioyield tester (Lu et al., 2005), which showed good correlation with MT firmness, and the bioyield probe was able to monitor the change in fruit firmness during postharvest storage. An improved version of a low-cost, portable bioyield tester was recently built, which has an onboard chip that automatically records and extracts bioyield parameters for each test. The improved tester is useful for monitoring the firmness of apples on the tree and for routine laboratory firmness measurements. Currently, commercial sonic and impact firmness measurement devices are available for measuring fruit firmness. These devices seem to work better on softer fruits such as peaches and pears, but their correlation with MT firmness for firm fruits such as apples is low or inconsistent (Shmulevich et al., 2003). Compared to the sonic or impact method, the bioyield testing method is simple and inexpensive in instrumentation. However, the bioyield tester is not suitable for fruits that do not exhibit the bioyield phenomenon and can also be a problem when rapid firmness measurements are required.

Conclusions

Finite element analyses demonstrated that a probe with a soft rubber tip of no less than 2 mm diameter and an elastic modulus comparable to or less than that of the apple fruit would produce a uniform stress distribution over the contact area. A smaller probe also tended to generate more uniform contact stress than large probes and reduced bruising damage to apples. Experimental tests showed that the probe with a rubber tip of 1.6 mm thickness could not detect the bioyield point for a higher percentage of apples. That probe also had a lower correlation with the Magness-Taylor (MT) firmness tester. The bioyield probe of 6.4 mm diameter with the soft tip of 3.2 mm thickness had a good correlation ($r = 0.828$) with MT firmness and should be the probe of choice. The bioyield test will be useful for measuring and monitoring apple fruit firmness in preharvest and postharvest operations.

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